Higher Order Statistical Analysis of Ocean Noise Measurements for Performance Prediction

Grant # N00014-95-1-0648

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First Analysis of SWellEX-3 Noise Characteristics

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Introduction

This report summarizes the first analysis of SWellEX-3 noise for nonstationarity and nonGaussianity. It is very important to understand these properties of the noise for the purpose of the design and performance analysis of various detection methods. A talk has been given on these results at the 130th International Meeting of the Acoustical Society of America, 27 Nov - 1 Dec 1995, in St. Louis, MO. The transparencies from the talk are in Appendix A of this report. In addition to the basic issues of characterizing the nonstationarity and nonGaussianity of the noise, it is also important to relate the noise characteristics to the shipping "fingerprint" in the area, to the extent possible. Radar shiptrack data are available for the latter purpose.

Rather than simply applying standard tests initially, very intuitive and graphical tests were designed to inform our understanding of the nature of the nonstationarity and nonGaussianity of the noise and to make clear which tests would be most appropriate and what other analysis might be necessary to raise our understanding to new levels. It should be stated from the outset that significant nonstationarity and possibly nonGaussianity have been found, and these results are given in the following. It also appears that the nonstationarity may be frequency dependent in terms of the amount of changes in the moments occurring over time, and that the analysis will not be complete until moment sampling issues are studied and aliasing is ruled out. The frequency of change being addressed here is of the noise moments with time, not simply that of the unanalyzed original data, although the two are of course related. In particular, the time variations of the four lowest order noise moments are the major properties being investigated initially for nonstationarity. It has also become clear that there are significant differences between a phone in the middle of the water column and one near the bottom. Specifically, the noise at the bottom hydrophone seems closer to Gaussian than the noise in the middle of the water column, perhaps caused by more averaging of the ship noise propagation paths at the bottom hydrophone. This can be investigated by establishing the relation of phone positions to the acoustic propagation paths in the experiment environment, recognizing the modal nature of the ocean waveguide and the multipath arrivals. It should be emphasized that this is a preliminary finding, and possible differences between phones in flow noise, phone motion, and other effects have not yet been considered, as pointed out by MPL scientists.

The first analysis involves three minute segments of hydrophone data sampled at 1/1500 sec. This data length is long enough to perform meaningful nonstationarity analysis and short enough to perform exploratory and first calculations in a reasonable time. Data selection and calibration were accomplished with significant help from personnel at MPL Scripps, in particular Drs. Gerald D'Spain and William Hodgkiss. Data were selected corresponding to low, moderate, and high shipping. The selected data segments are identified on page A6 in Appendix A. This Appendix contains the slides of the ASA talk on pages A1 through A21. Ship tracks for these three data segments (low, moderate, high) are given on pages A7 through A9. Initially three phones are selected for comparison, numbers 2, 43, and 61. As shown in Figure A5, phone 2 is at a depth of 192 m near the bottom of the 198 m water column, phone 43 is at 116 m depth, and the highest phone considered, number 61, is at 82 m depth, about halfway down the water column.

Data Preprocessing

Dominant FLIP noise lines have been removed from all data after applying the data calibration specified by MPL. This is done by substituting average Fourier transform values for the FLIP noise spectral peaks. There are several smaller sources of contamination from various pumps, motors, etc., aboard FLIP. We have obtained information on these sources from MPL and are examining data spectra to determine for which lines removal is required.

Moment Variation with Time

Initial information on data stationarity is obtained from "Christmas" plots, those containing red and green curves shown in Figures A10 through A15. These plots indicate the change of the first, second, third, and fourth moments with time over the course of three minutes. A number of cases are included to illustrate important points in the analysis. The figures can be used to investigate the depth dependence of the nonstationarity and the frequency variation of the nonstationarity, and to compare the different levels of shipping noise. The channel number corresponds to the phone, while the file number corresponds to the noise level. File 1 is the moderate noise, file 2 is the high noise, and file 3 is the low noise. It should be noted that shipping traffic in the area is always significant, and the terms moderate, high, and low are only relative. Three data processing windows, applied with corresponding overlaps, were selected to do the first study of the frequency variation of the nonstationarity. Each window was arbitrarily chosen to have an overlap of 50 percent of its width to determine the placement of the window center and therefore the time sampling rate of the nonstationarity time variation as indicated by the moments. This was done to have a starting point that corresponds with common practice, but our immediate next step of analysis will be to move the windows of each size by only one data time sample point at a time and to take Fourier transforms of the resulting moments versus time, to get maximum possible insight into the frequency variation of the nonstationarity. In particular, this type of analysis can provide very convincing, if not 100% conclusive, evidence about aliasing and appropriate sampling rates for the time variation of the nonstationarity. Even the initial analysis has suggested some very interesting possibilities.

Because the statistical variability of the moments with time (green curve) is high, it is difficult to use visual inspection to decipher trends. A Gaussian smoothing procedure (convolution of the moments with a Gaussian) is used to overcome this difficulty. To be sure that the smoother does not introduce nonuniform effects on the time variation studied with different window widths, the time width of the Gaussian smoother is kept the same for all plots. Since the Gaussian smoother is smoothing plots which sample the time variation of the moments every 750 time points, every 75 time points, and every 7 time points, this means that different numbers of points are included in the Gaussian smoother for each of these cases. As mentioned, the sampling time interval for the time points in the original data is 1/1500 sec.

Additional important information on the figures is the mean and standard deviation of each moment over time as given in the individual figure titles. These can be used to compare the variation from phone to phone, etc. They are also collected later in the report into tables, where they are compared to the values for Gaussian distributed noise to give important information on the Gaussianity of the noise, or the lack of it.

Figures A10 at phone 43 and A11 at phone 2, for the moderate shipping noise three minute window, are used to compare the depth dependence of the nonstationarity. As can be seen from the two figures, there is nonstationarity in all the moments, except that the first and third moments for phone 2 have less than half the standard deviation of those of phone 43. From these figures, no depth dependence of the nonstationarity should be claimed, although there is a slight suggestion of less nonstationarity in the odd moments for the bottom phone. Greater upper phone motion or flow noise is a possible source of this difference.

To study the frequency variation of the nonstationarity with time, we compare the plots which show the results of sampling every 750 points, every 75 points, and every 7 points. These are Figures A11 through A13, and are all done for phone 2 in the moderate shipping noise time window. The 750 point sampling interval corresponds to the 1500 point time window, the 75 point sampling interval to the 150 point time window, and the 7 point sampling interval to the 15 point time window. As might be expected, the statistical time variation of the unsmoothed moments includes higher frequency variation with finer sampling. The standard deviation clearly increases with finer sampling, indicating that as the higher frequency time variations of the moments are observed, additional variability is included. In future analysis the windows will be moved one sample point at a time across the data and the Fourier transforms of the moment variations will be studied carefully for each window size. This analysis will be combined with the more detailed window size analysis to be described later in this report and with a similar analysis for simulated stationary Gaussian noise. After this and other tests we can speak more definitively about the nature of the nonstationarity.

The last series of "Christmas" plots to be compared, Figures A10, A14, and A15, illustrates the effect of different levels of shipping noise on the nonstationarity for phone 43 with the 1500 point window. By examining the standard deviations of the moment curves, one can conclude that the nonstationarity for moderate and high shipping is comparable, whereas that for low shipping is significantly higher. This is perhaps not surprising since low shipping noise is expected to be more episodic, whereas higher shipping noise in some cases might be expected to have more consistency over time due to the larger diversity of sources.

Effect of Processing Window Size

The graphs on pages A16 and A17 indicate the effect of processing window size on the means and standard deviations of the four moments for three minutes of moderate noise on phone 2. Processing window sizes of up to 20,000 time points are included. In A16 the variation of the mean of each of the four moments with processing window size is shown. The mean gradually increases with increasing window size, with some fluctuation, until a window size of about 8,000 to 10,000 points. At larger window sizes there is significant fluctuation in three of the moments, possibly due to the decreasing number of samples available for averaging. This can be tested by taking data segments which are longer than three minutes.

The standard deviation, shown on page A17, is more stable with changing window size at the larger processing windows than the mean. It too increases significantly as the window size increases, up to about 8,000 to 10,000 point windows. Above this window size the second through fourth moments increase slightly.

While it is important to work with long enough windows so that the moment calculations are not a function of window length, it may not be possible to do this for all analyses. In particular, if stationarity only exists over much shorter times, then the processing windows will have to be short to do a proper analysis.

Gaussianity

To determine in a first test whether the noise statistics are Gaussian, the noise moments are compared to Gaussian noise moments in the tables on pages A18 and A19. Simulated Gaussian noise of the same length as the selected experimental noise segments is used to calculate the Gaussian moments. Phone 61 and phone 2 at all three noise levels are used for the examples. In each case the mean and standard deviation are calculated for the 359 moment values in a three minute data segment which has its moments calculated in each 1500 data sample window, with the windows overlapped by 50%. The Gaussian noise is generated to have an average variance equal to the variance of the three minute data segment at each noise level for each phone. Because the first moments are relatively small, the Gaussian data second moment will also be approximately equal to the measured noise second moment. Then by comparing the higher moments at each noise level for each phone, tentative conclusions can be reached about the Gaussianity or nonGaussianity of the noise. It must be emphasized that this test has real limitations due to the nonstationarity. In particular, our findings of average nonGaussianity over the three minute intervals does not rule out local Gaussianity in shorter time intervals, or more Gaussian behavior for processing windows longer than 1500 points (1 second).

The summary table on page A18 is for phone 61 in the middle of the water column. A table line of moments for low-noise stationary Gaussian simulated data (having the same variance as the low-noise data) precedes the line for the low-noise data moment summary. These are followed by similar lines for moderate noise and high noise. Each table box contains the mean and the standard deviation of the 359 moments (as explained above) for the appropriate three minute segment of the actual data or the corresponding simulated Gaussian data. A like table for phone 2 at the bottom of the water column is on page A19.

We note that, while the mean of the second moments, m2, of Gaussian and actual data are approximately equal for the phone 61 data, the standard deviations of m2 are about ten times as large for the actual data as for the Gaussian. This means that there is more variation among the different 1500 point windows in m2 for the data and suggests nonstationarity, although the standard deviations are still small compared to the means, being little more than one half at the largest for the high shipping data. It is possible to have the data Gaussianly distributed within individual 1500 point windows, but with changing variance among the windows.

The higher moments provide checks on the Gaussianity of the data. The mean of the third moments, m3, of the data is about 3, 100, and 20 times as large as that of the Gaussian for low, moderate, and high noise, respectively. This indicates considerable skewness in the data density function compared to a Gaussian. As mentioned previously, this may be due to a systematic array problem rather than being a property of the noise itself. The standard deviation of m3 is about 3.6, 5, and 1 times that of the Gaussian, respectively.

The average fourth moments, m4, for data and Gaussians are about equal, suggesting that if the deviations in the third moments are not intrinsic to the noise, the noise may be fairly Gaussian. The large differences in the average standard deviations of m4 between stationary Gaussian data and actual data again suggest nonstationarity, but the data m4 standard deviations are still smaller than the m4 means except the high noise case, for which they are about equal.

For the near-bottom phone 2, the data seem amazingly Gaussian from comparing the means of the moments m2, m3, and m4. The largest difference is a factor of about two for m3 in the low noise case. All the other means are considerably closer than this for Gaussian data and actual data, suggesting that the data at this phone are Gaussian in 1500 point windows, though not necessarily in longer or shorter windows. Data standard deviations for m2 range from about 4.5 to 7 times those of a Gaussian, for m3 from about 1.5 to 3, and for m4 from about 3.5 to 6, suggesting nonstationarity, although all the standard deviations for m2 and m4 are less than the means. The standard deviations for m3 are large compared to the means for the both Gaussian and actual data.

Visit to ARL

Two investigators, Lisa Pflug and George Ioup, spent a very fruitful day visiting Drs.

Gary Wilson and Martin Barlett at the University of Texas at Austin Applied Research Laboratory. They were given a presentation on the ARL method of transient detection and spent the remainder of the day discussing topics such as types of transients, stationarity requirements, available transient data sets, other transient detection methods, and related topics. The successful ARL transient detection method is especially effective for modal-type transients, but not as effective for broadband transients. It requires stationarity for about 100 successive processing windows.

As a result of these discussions, a better understanding was gained of the important noise analyses for the effects of noise characteristics on transient detections and of the evaluation of various detectors.

Current investigations

One important aspect of current research is to investigate the frequency dependence of the nonstationarity by considering the Fourier transform of the finely sampled moments calculated with various window sizes.

We are removing other sources of data contamination besides the dominant FLIP lines. These include 1) the smaller sources of contamination aboard FLIP, which produce line spectra, and 2) flow noise, which contaminates low frequencies up to 10 Hz. For the latter we use a stopband ninth-order Butterworth filter to suppress all low frequencies.

We are also applying standard tests of stationarity and Gaussianity to the data. For stationarity, the Hurd and Gerr (1991) test and tests of moment transforms for off-line (second moment) and out-of-plane (third moment) components chould prove informative. For Gaussianity, the Tsatsanis and Giannakis time domain test (1994) and the Hinich transform domain test (1982) may provide useful information, in addition to the well-known Kolmogorov-Smirnov test for goodness of fit.

We are also considering detection statistics to be used for nonstationary noise and how to simulate the noise, especially matching the color of the noise and its nonstationary properties.

A paper describing our more recent work, "Moment Analysis of Ambient Noise Dominated by Local Shipping" has been accepted for presentation at the 8th IEEE Signal Processing Workshop on Statistical Signal and Array Processing and publication in the Proceedings. Only about half the submitted papers were accepted. A copy will be supplied to the Program Manager/Officer as soon as it is available.

References

Georgios B. Giannakis & Michail K. Tsatsanis, 1994, Time-Domain Tests for Gaussianity and Time-Reversibility, IEEE Trans. on Signal Processing 42, 3460-3472.

Melvin J. Hinich, Testing for Gaussianity and Linearity of a Stationary Time Series, 1982, J. Time Series Anal. 3, 169-176.

Harry L. Hurd and Neil L. Gerr, 1991, Graphical Methods for Determining the Presence of Periodic Correlation, J. Time Series Anal. 12, 337-350.

Preliminary Analysis of SWellEX-3 Noise Characteristics

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Motivation

Assumptions about the statistics of ambient noise are often required to apply transient detection algorithms succesesfully. While assumptions of Gaussianity and stationarity may be appropriate in deep water areas, they may not be appropriate in littoral areas.

It is important to understand the restrictions imposed by the noise on transient and other detectors in shallow water. For higher order statistical detectors, it is also important to consider the higher order moments of the noise to evaluate and predict detector performance.

Issues

1) Over what time periods does the ambient noise in a port area appear stationary?

2) What are the first, second, and higher order moments of the noise?

3) How do the statistics of the noise change over time, and can the changes be related to the shipping "fingerprint" of the area?

SWellEX-3

Place and Time: Port of San Diego, July-August 1994.

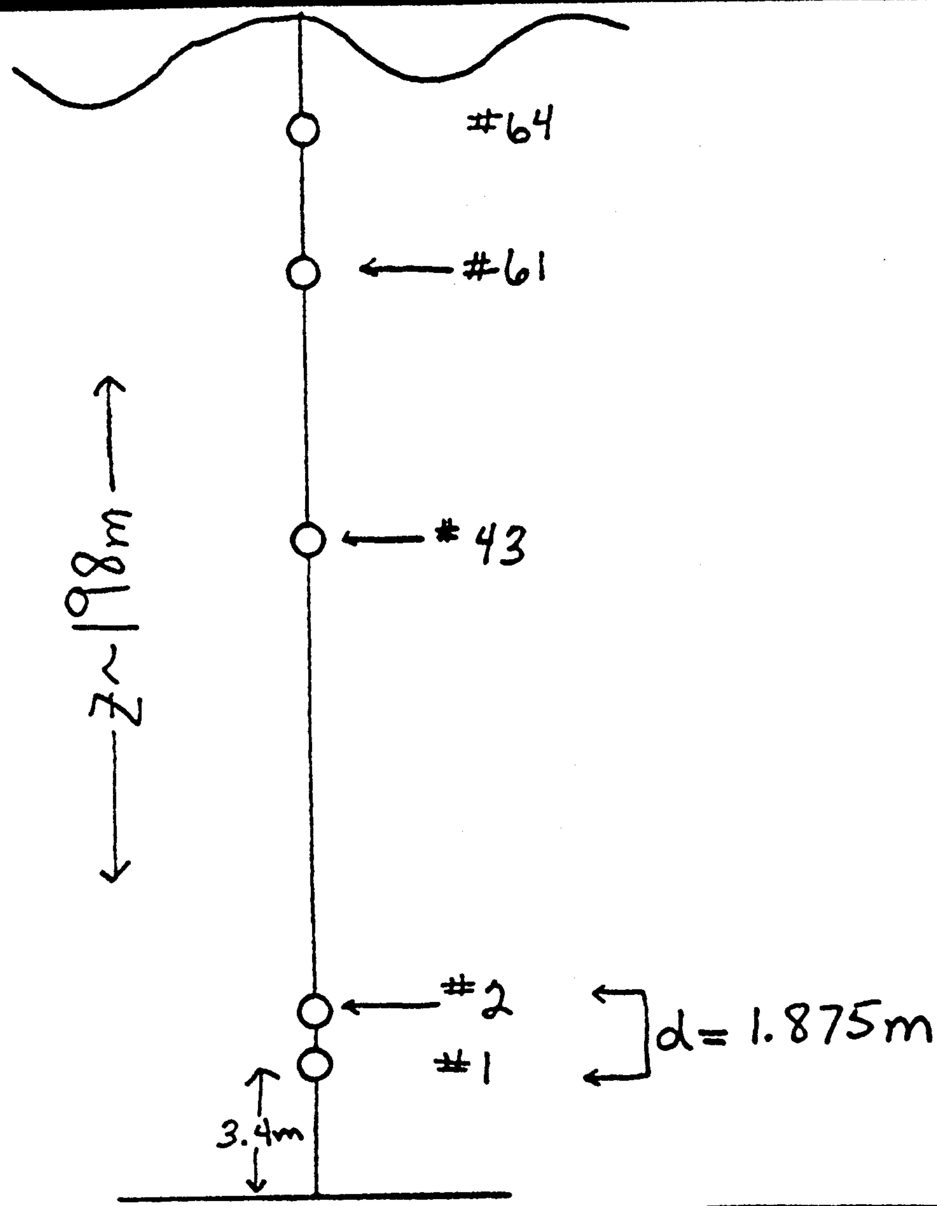
Who: NRaD, MPL, and NRL

Objective: Improve passive detection and localization of quiet targets in shallow water.

Data: Two full weekends of ambient noise.
Radar ships tracks (20 nmi).

Sensors: MPL's SRP 64-element array.
1500 samples/sec.

SRP Array



Phone #	Appx. Depth
2	192 m
43	116 m
61	82 m

Data Sets

3-minute segments of hydrophone data:

<u>Low shipping</u>

Julian Day 212, Local Time: 11 hr, 13 - 16 min

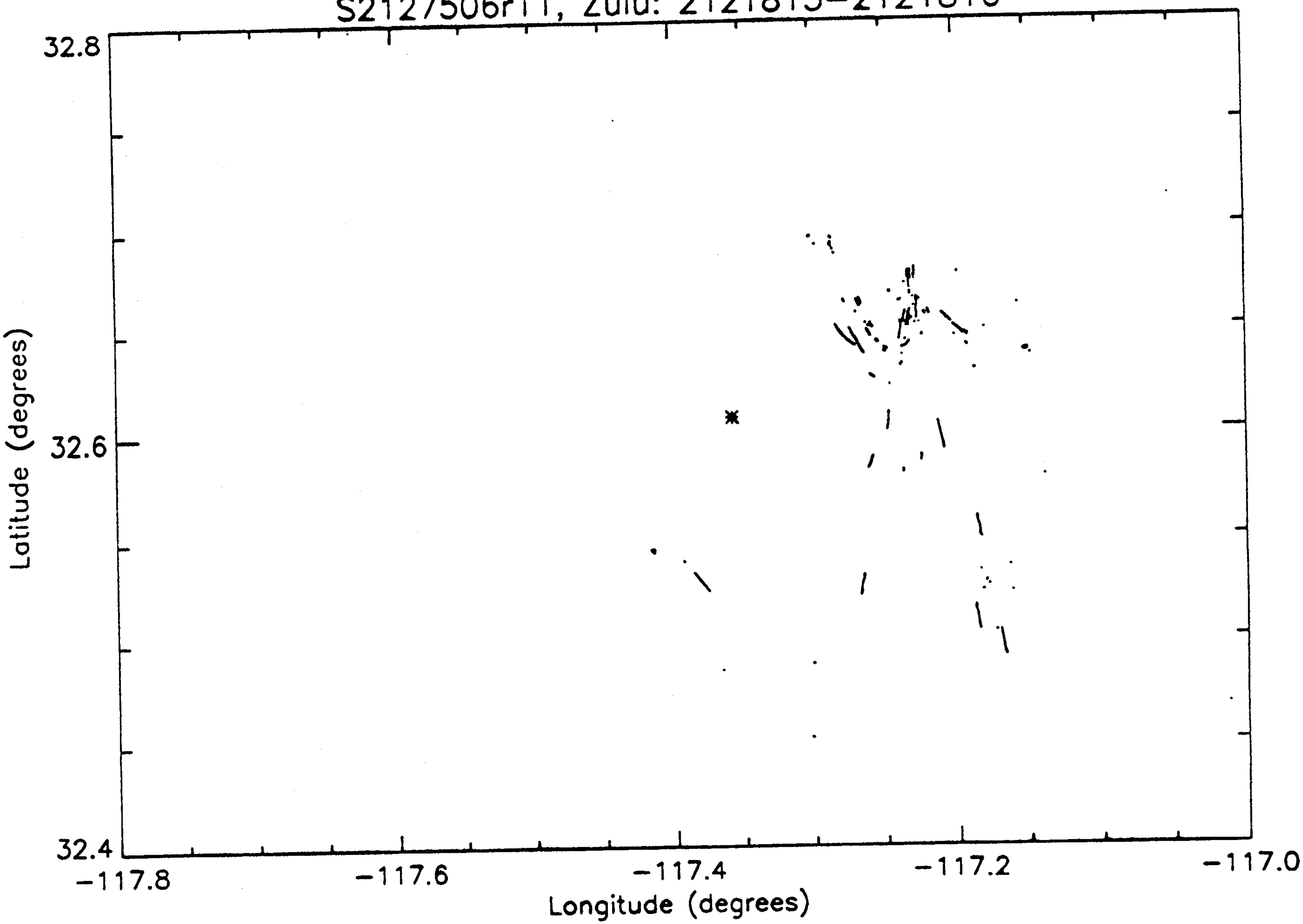
<u>Moderate shipping</u>

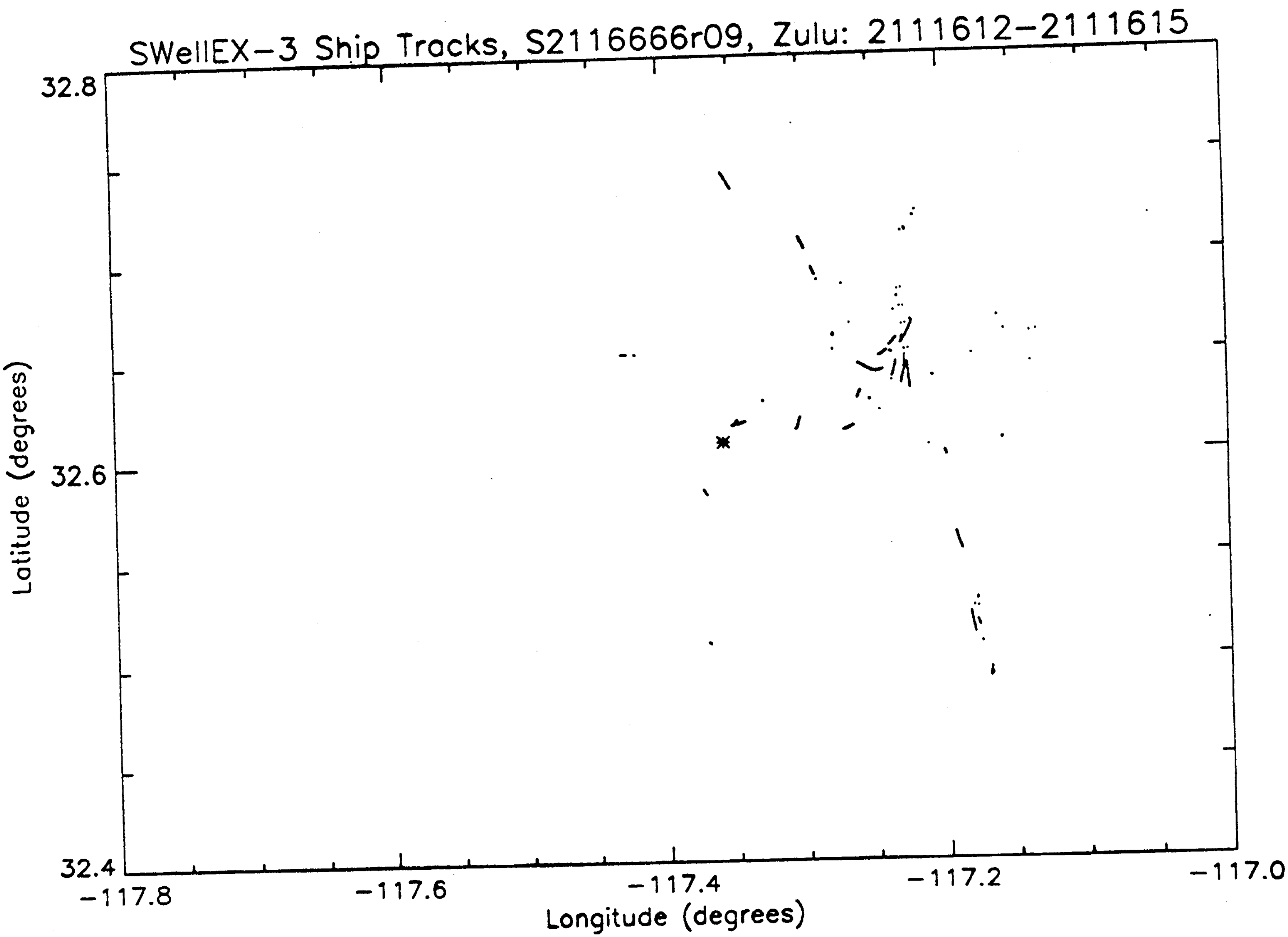
Julian Day 211, Local Time: 16 hr, 12 - 15 min

<u>High shipping</u>

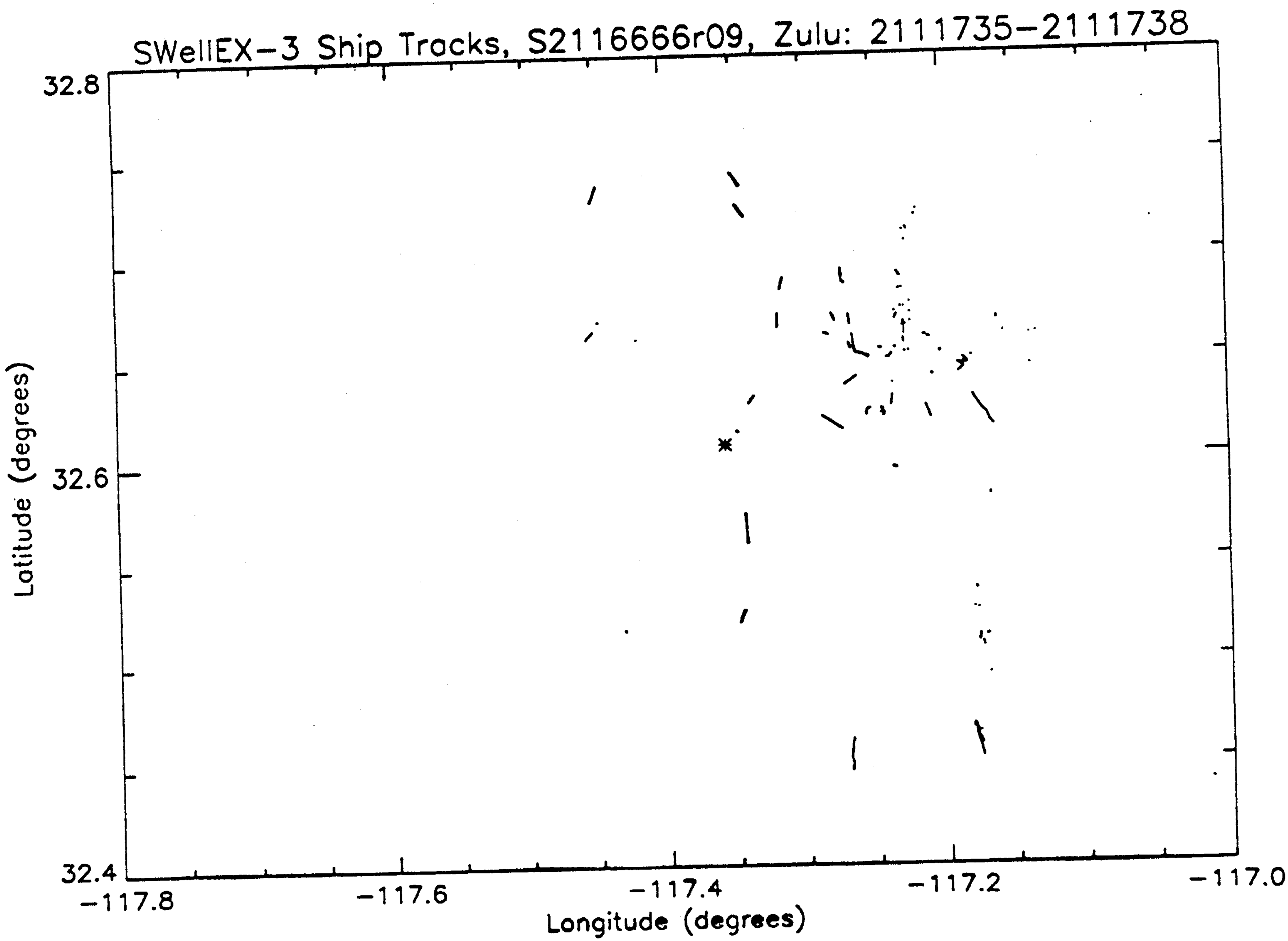
Julian Day 211, Local Time: 17 hr, 35 - 38 min

S2127506r11, Zulu: 2121813–2121816





SWellEX-3 Ship Tracks, S2116666r09, Zulu: 2111612-2111615
32.8
32.6
32.4
Latitude (degrees)
-117.8
-117.6
-117.4
-117.2
-117.0
Longitude (degrees)


SWellEX-3 Ship Tracks, S2116666r09, Zulu: 2111735-2111738
32.8
32.6
32.4
Latitude (degrees)
-117.8
-117.6
-117.4
-117.2
-117.0
Longitude (degrees)

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Channel number: 43

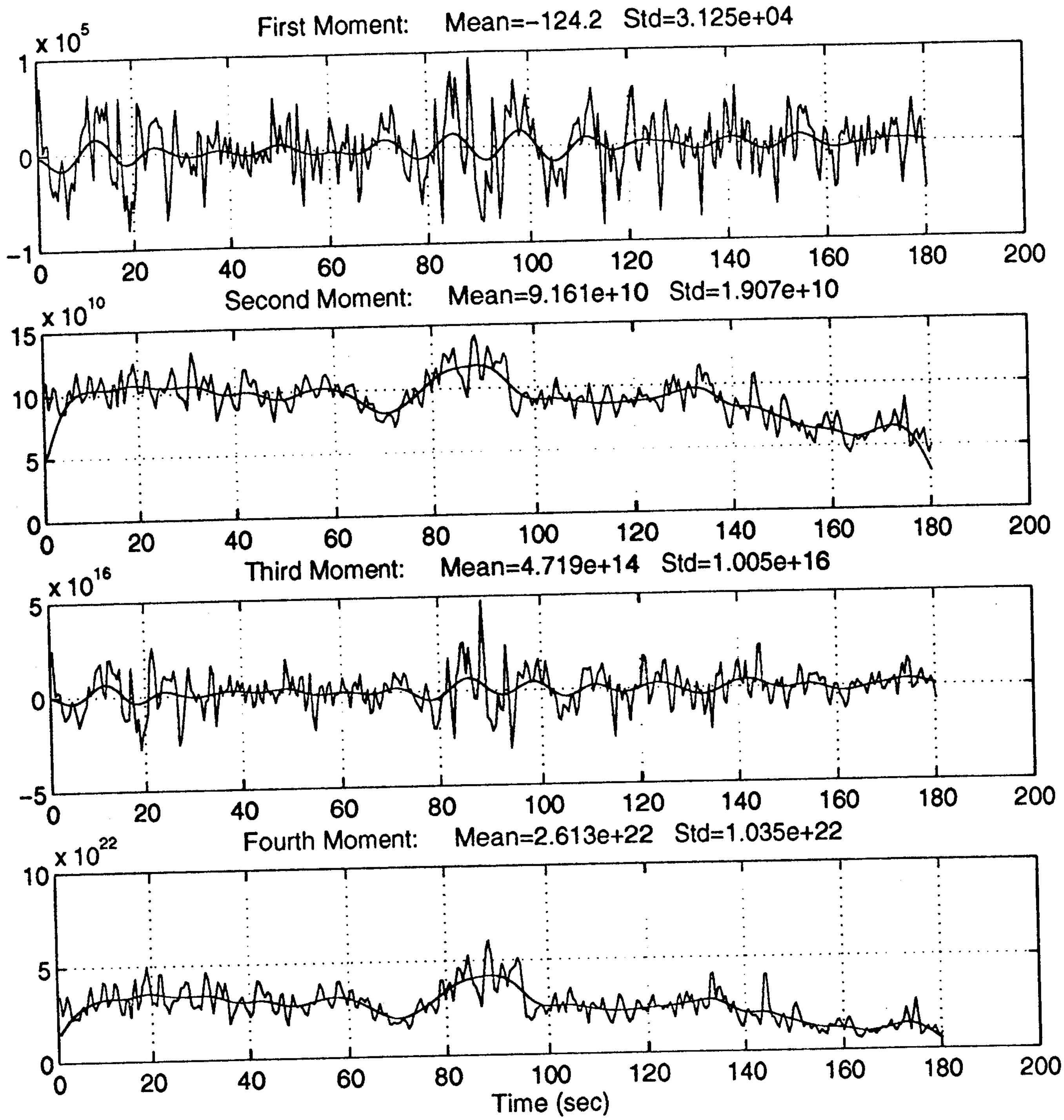
Processing window: 1500 points

Percent overlap: 50%

Sampling frequency: 1500

Gaussian smoother: 30 points

Date: 22–Nov–95



Filename: chan2_file1

Channel number: 2

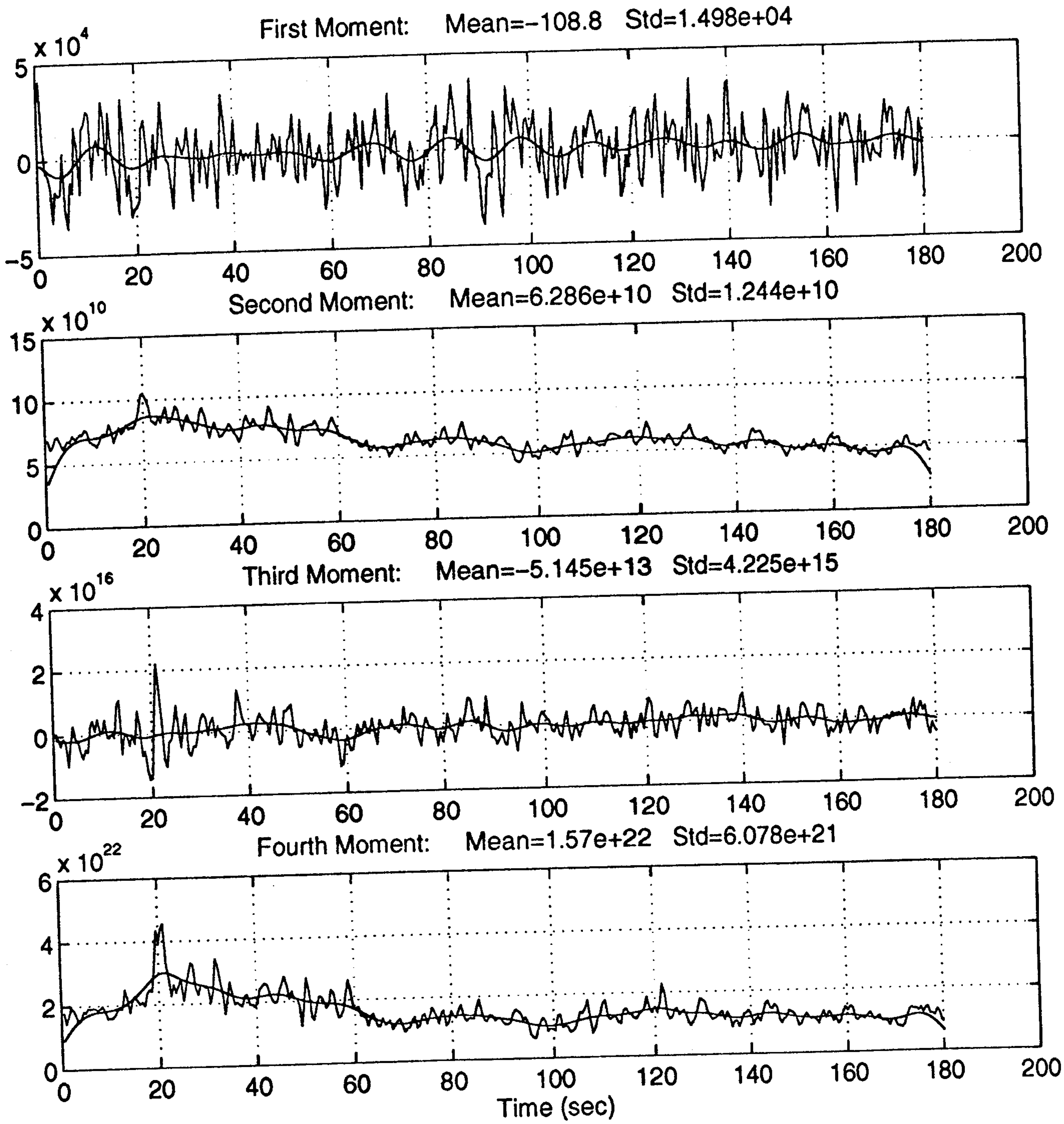
Processing window: 1500 points

Percent overlap: 50%

Sampling frequency: 1500

Gaussian smoother: 30 points

Date: 21-Nov-95



Filename: chan2_file1

Channel number: 2

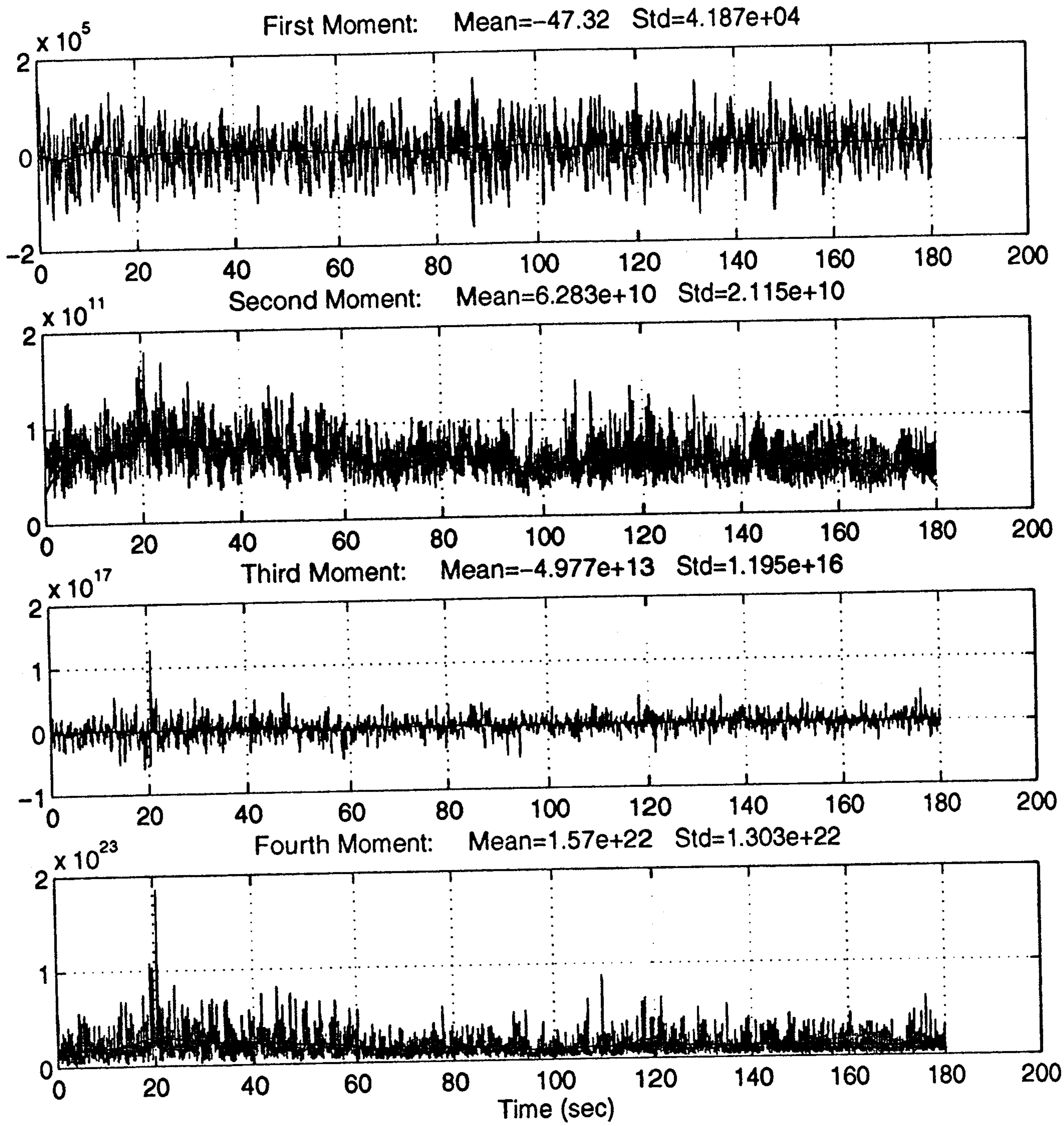
Processing window: 150 points

Percent overlap: 50%

Sampling frequency: 1500

Gaussian smoother: 300 points

Date: 21-Nov-95



Filename: chan2_file1

Sampling frequency: 1500

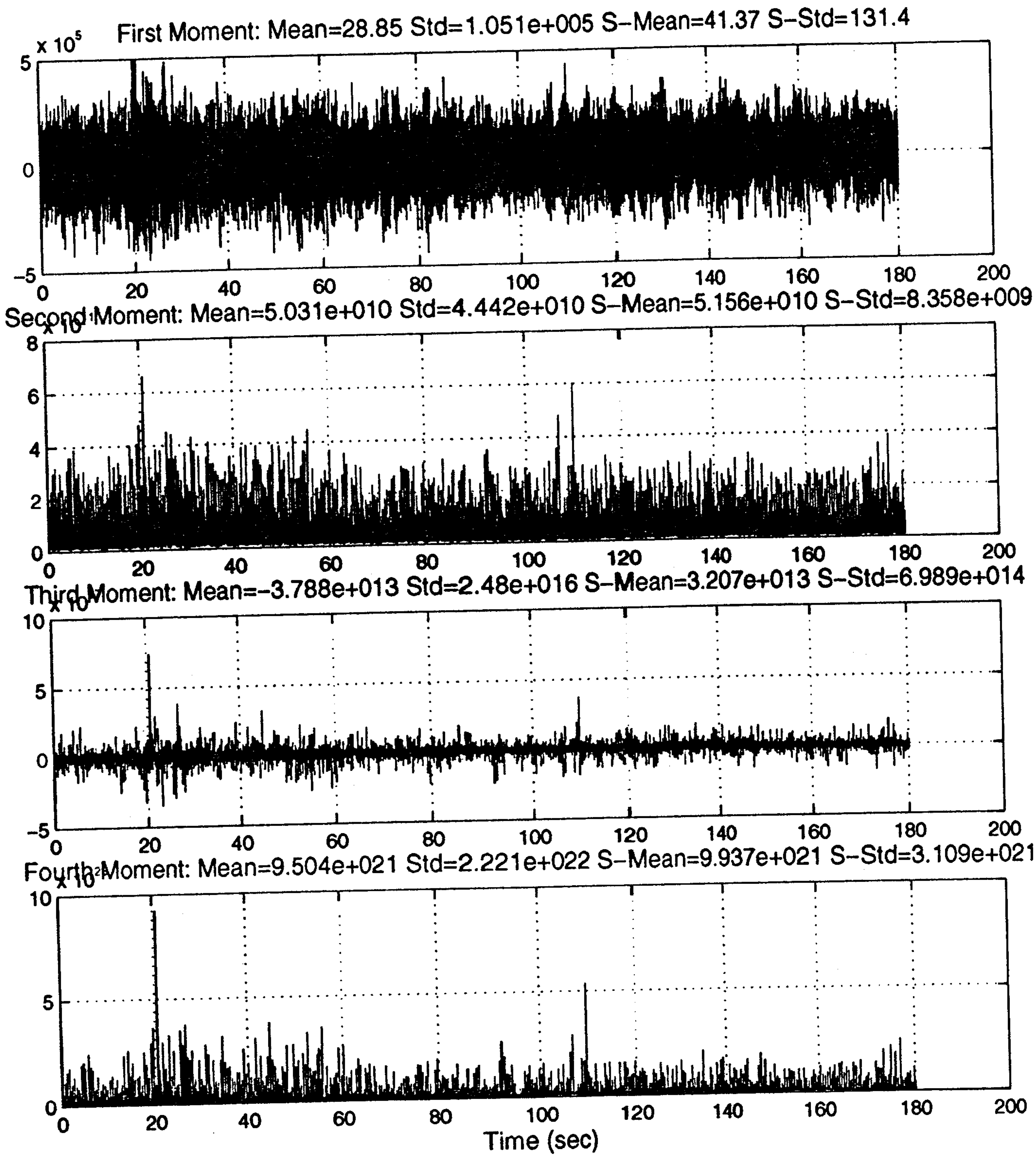
Channel number: 2

Gaussian smoother: 3214 points

Processing window: 15 points

Date: 5-Feb-96

Percent overlap: 46.67%



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Channel number: 43

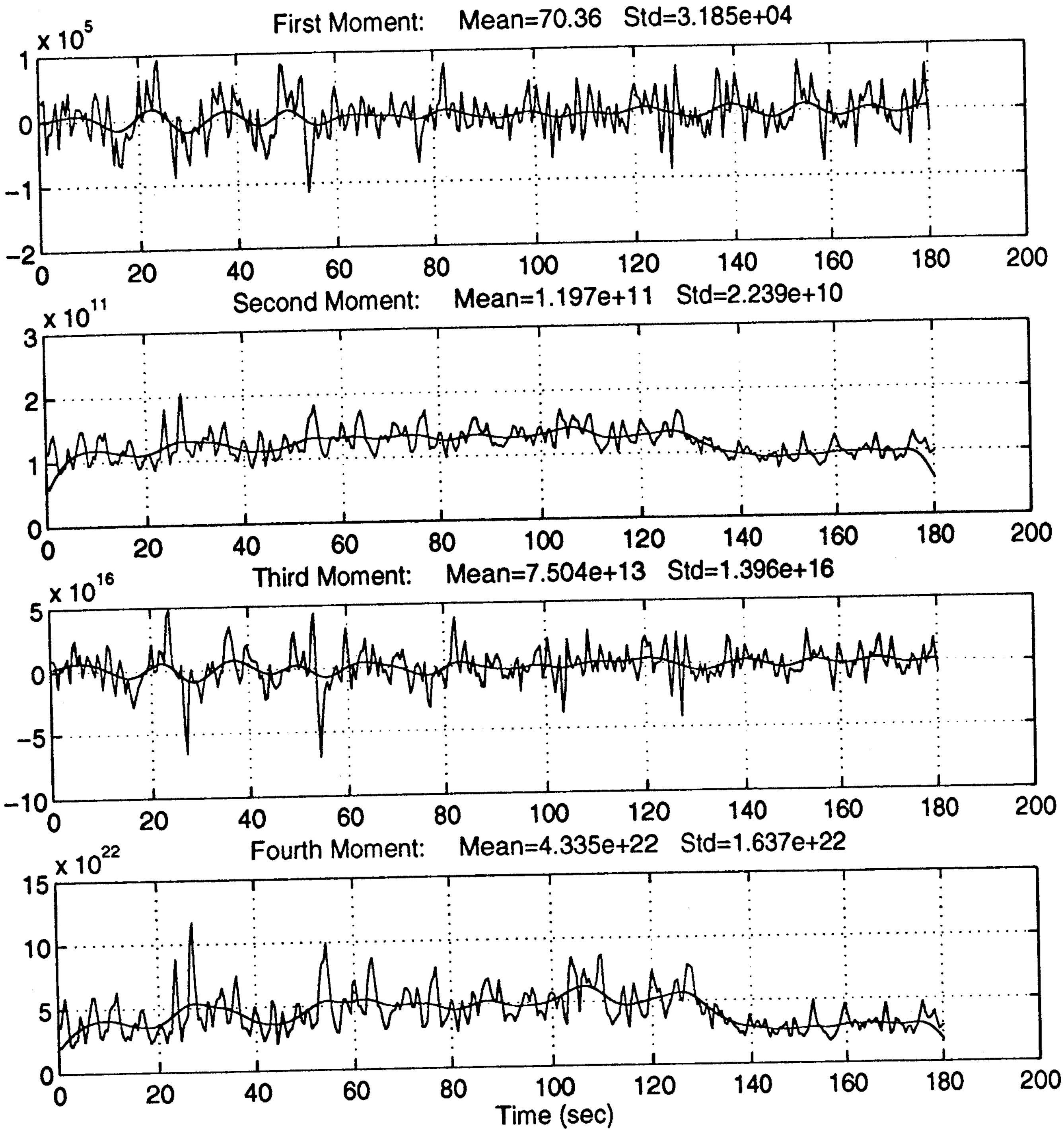
Processing window: 1500 points

Percent overlap: 50%

Sampling frequency: 1500

Gaussian smoother: 30 points

Date: 22-Nov-95



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Channel number: 43

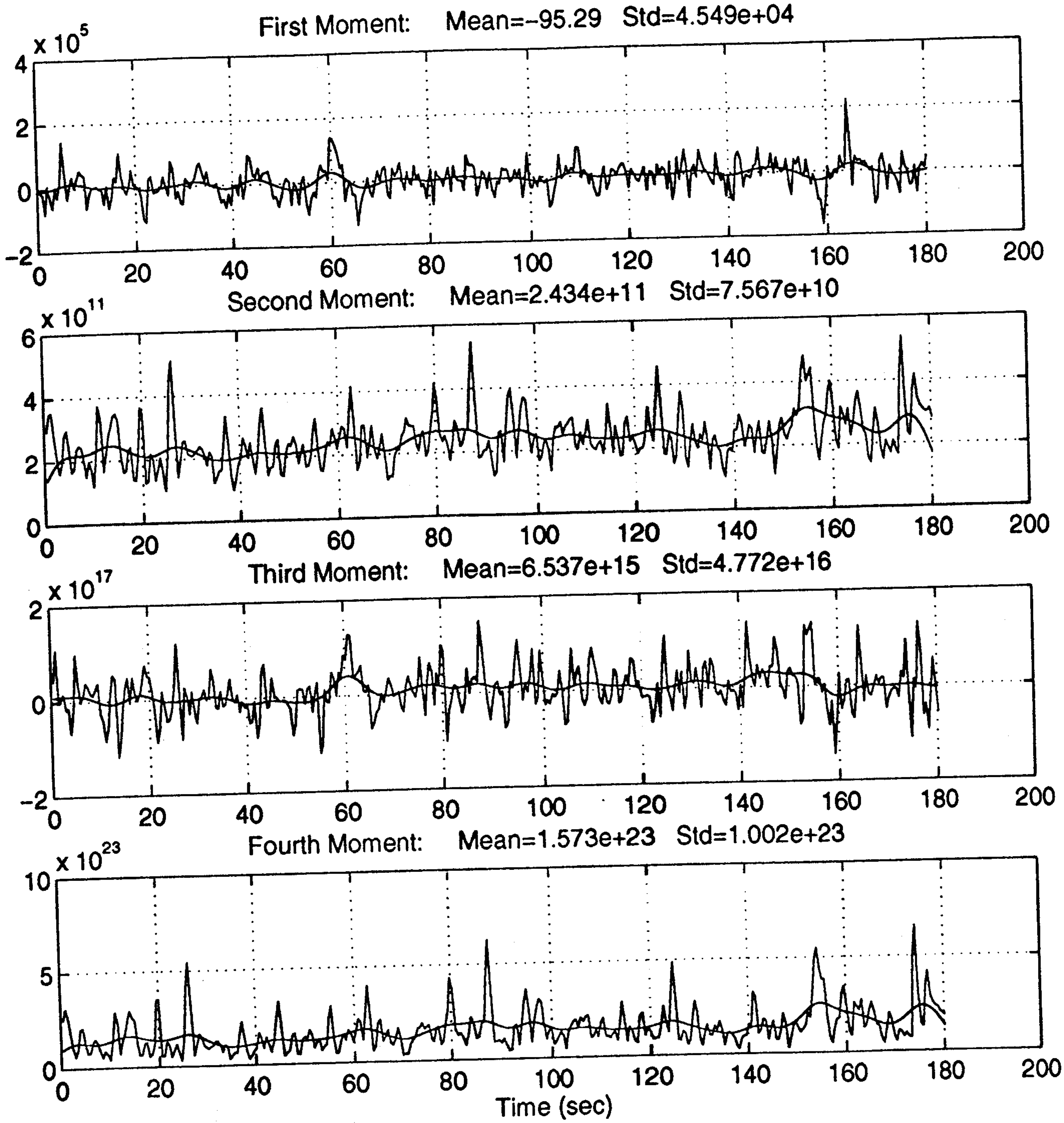
Processing window: 1500 points

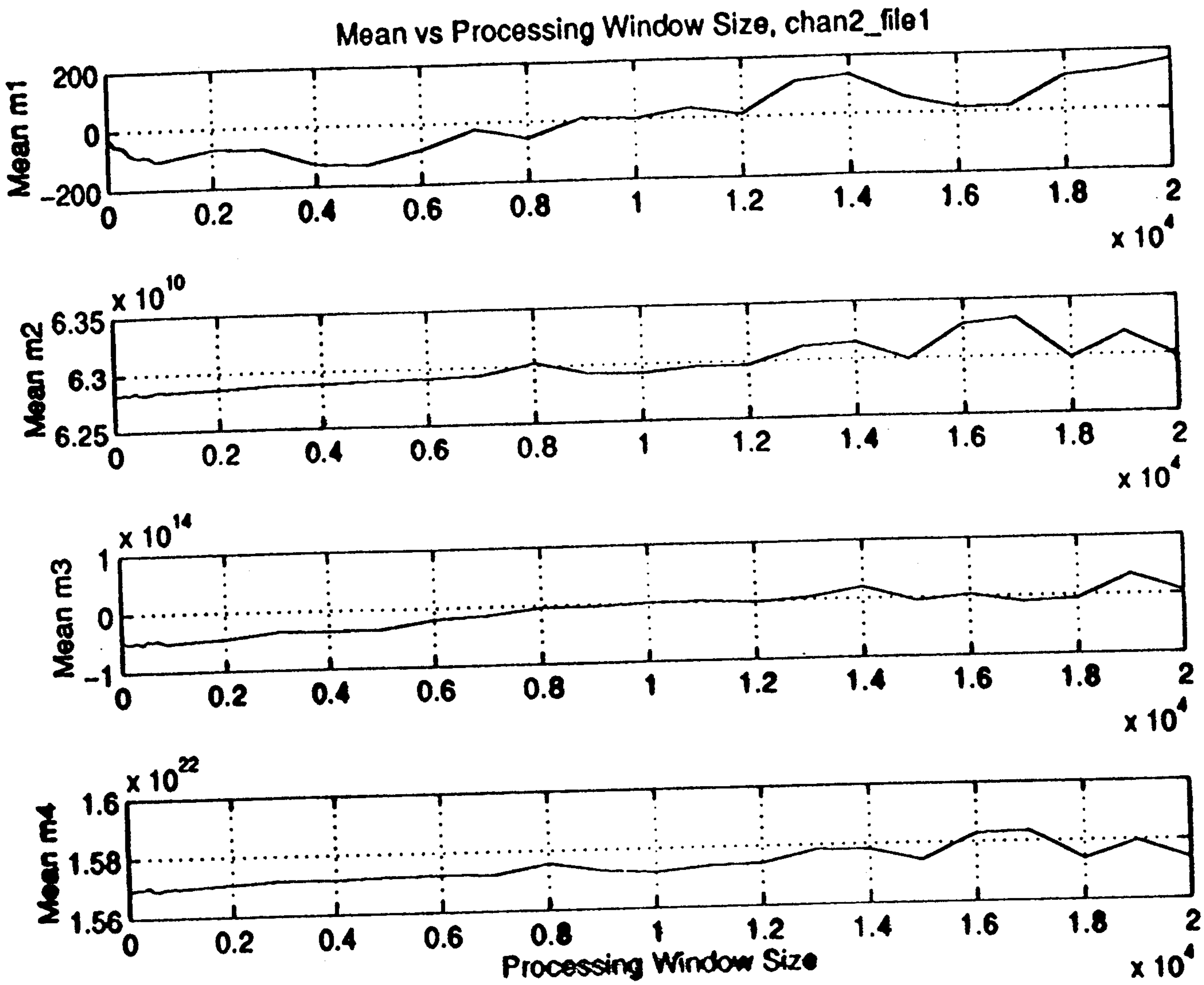
Percent overlap: 50%

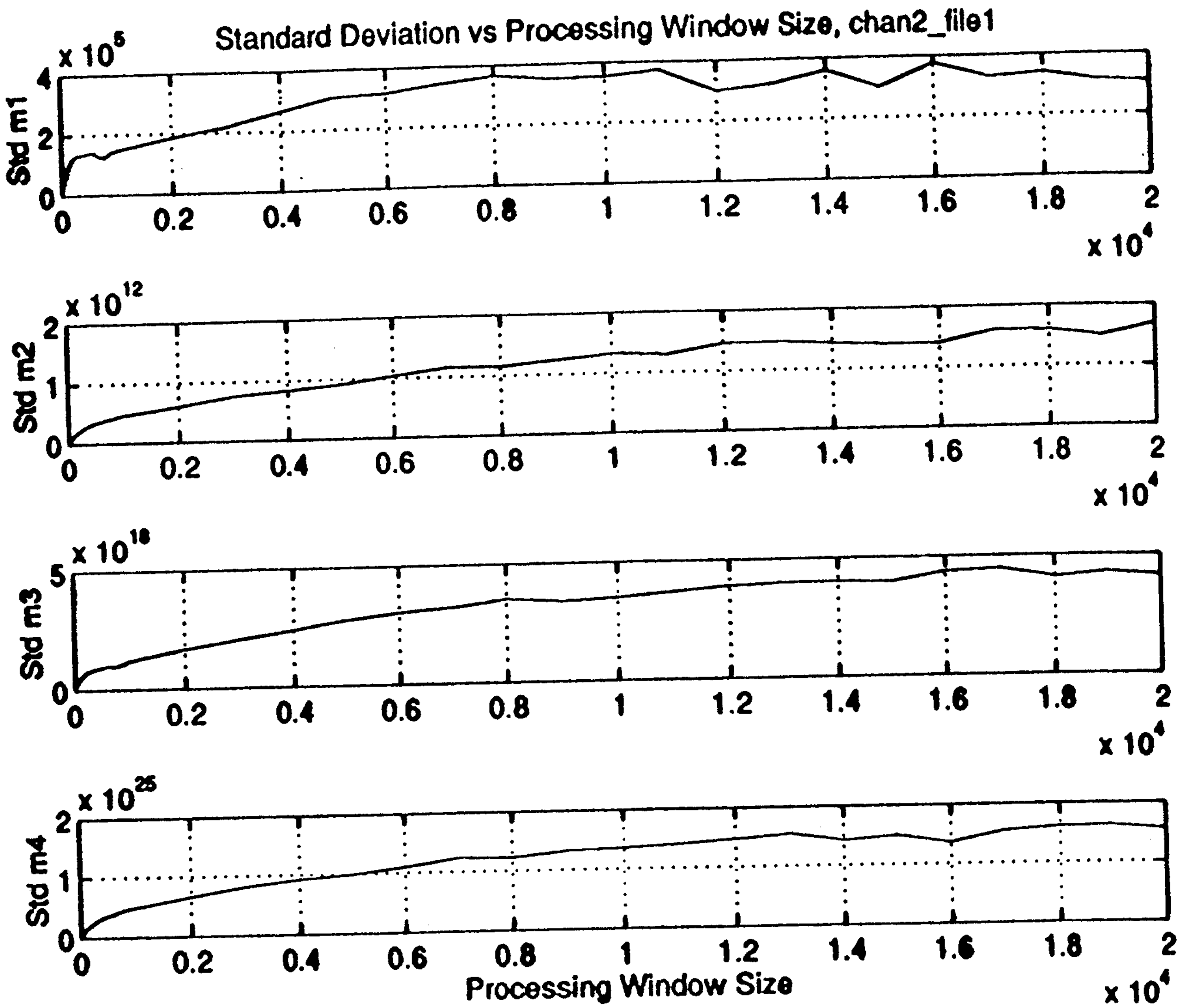
Sampling frequency: 1500

Gaussian smoother: 30 points

Date: 22-Nov-95




Mean vs Processing Window Size, chan2_file1
Mean m1
200
0
-200
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
x 10^4
x 10^10
Mean m2
6.35
6.3
6.25
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
x 10^4
x 10^14
Mean m3
1
0
-1
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
x 10^4
x 10^22
Mean m4
1.6
1.58
1.56
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Processing Window Size
x 10^4



Standard Deviation vs Processing Window Size, chan2_file1
x 10^5
Std m1
0
2
4
x 10^12
Std m2
0
1
2
x 10^18
Std m3
0
5
x 10^25
Std m4
0
1
2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
x 10^4
Processing Window Size

Summary Table - 3.1

1500 Point Processing Window

Channel 61 (top)	m1 (mean std)	m2 (mean std)	m3 (mean std)	m4 (mean std)
Gaussian (low)	1840 2.584 e+04	9.677 e+11 3.874 e+10	-1.445 e+15 1.032 e+17	2.812 e+24 2.491 e+23
Low Shipping	-468.1 1.067 e+05	9.664 e+11 3.099 e+11	-4.229 e+15 3.741 e+17	2.512 e+24 1.631 e+24
Gaussian (moderate)	903.7 3.185 e+04	1.673 e+12 5.730 e+10	3.081 e+15 2.277 e+17	8.363 e+24 6.893 e+23
Moderate Shipping	215 1.437 e+05	1.670 e+12 5.300 e+11	3.714 e+17 1.365 e+18	8.283 e+24 5.746 e+24
Gaussian (high)	1465 8.908 e+04	1.331 e+13 4.811 e+11	3.227 e+17 4.073 e+18	5.301 e+26 4.749 e+25
High Shipping	-2546 4.431 e+05	1.337 e+13 6.897 e+12	6.483 e+18 3.744 e+18	6.174 e+26 7.135 e+26

Summary Table - 1.1

1500 Point Processing Window

Channel 2 (bottom)	m1 (mean std)	m2 (mean std)	m3 (mean std)	m4 (mean std)
Gaussian (low)	-316.6 5.589 e+03	5.053 e+10 2.015 e+09	-1.549 e+13 1.121 e+15	7.671 e+21 7.002 e+20
Low Shipping	-75.67 1.787 e+04	5.069 e+10 1.524 e+10	-2.910 e+13 3.015 e+15	6.559 e+21 3.638 e+21
Gaussain (moderate)	-660.2 6.856 e+03	6.300 e+10 2.182 e+09	-4.585e+13 1.773 e+15	1.190 e+22 9.771 e+20
Moderate Shipping	-108.8 1.498 e+04	6.286 e+10 1.244 e+10	-5.145 e+13 4.225 e+15	1.570 e+22 6.078 e+21
Gaussian (high)	-228.5 6.661 e+03	6.216 e+10 2.113 e+09	-1.341 e+14 1.448 e+15	1.162 e+22 1.021 e+21
High Shipping	20.44 1.984 e+04	6.919 e+10 9.236 e+09	-1.137 e+14 4.075 e+15	1.165 e+22 3.615 e+21

Observations

Second and higher order moments appear to depend on the depth of the hydrophone.

Higher frequency ambient noise appears more stationary than the lower frequency noise. (Could there be an aliasing problem in the sampling of the moment variation in time?)

The standard deviation of the moments increases and stabilizes as the processing window size increases.

Future Work

Perform systematic study of relationship between higher order moments and phone depth.

Investigate frequency dependence of moments.

Analyze longer segments of data (30 minutes).

Apply K-S test to quantify nonGaussianity.

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13. ABSTRACT (Maximum 200 words)
This report summarizes the first analysis of SWellEX-3 noise for nonstationarity and nonGaussianity. It is very important to understand these properties of the noise for the purpose of the design and performance analysis of various detection methods. A talk has been given on these results at the 130th International Meeting of the Acoustical Society of America, 27 Nov - 1 Dec 1995, in St. Louis, MO. The transparencies from the talk are in Appendix A of this report. In addition to the basic issues of characterizing the nonstationarity and nonGaussianity of the noise, it is also important to relate the noise characteristics to the shipping "fingerprint" in the area, to the extent possible. Radar shiptrack data are available for the latter purpose.

Rather than simply applying standard tests initially, very intuitive and graphical tests were designed to inform our understanding of the nature of the nonstationarity and nonGaussianity of the noise and to make clear which tests would be most appropriate and what other analysis might be necessary to raise our understanding to new levels. Significant nonstationarity and possibly nonGaussianity have been found, and these results are given in the following. It also appears that the nonstationarity may be frequency dependent in terms of the amount of changes in the moments occurring over time, and that the analysis will not be complete until moment sampling issues are studied and aliasing is ruled out.

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